Australian sandy-beach ecosystems and climate change: ecology and management

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ABSTRACT

Despite their great socio-economic importance, sandy beaches have attracted little ecological research. This is unfortunate since, contrary to popular belief, they support diverse ecological assemblages whose species are mostly small and buried and which deserve protection as part of ecologically sustainable development (ESD). Moreover, the management of beaches and linked adjacent ecosystems is becoming increasingly important because of their vulnerability to burgeoning human pressures including climate change. Although there are large uncertainties involved, some of the climate-related environmental changes and their ecological consequences for sandy beaches are explored in this paper, some management issues discussed and research proposed.

Temperature-related changes include the likelihood that the geographical ranges of some species will change, some cool-adapted species will decline in abundance, possibly to extinction, and the rate of processes such as decomposition and photosynthesis will increase. The increasing acidification of the ocean may affect many beach species directly via reduced calcification and indirectly via changes to the phytoplankton on which some beach species depend for food. Changed hydrology may affect both nearshore primary productivity and the larval movements of many species. Increased storminess may change the morphodynamic state of beaches with consequent effects on the diversity, abundance and composition of beach assemblages. The combination of storm surges and sea-level rise may enhance erosion rates, the most extreme effect being the total loss of sandy beach habitat, especially if sea-walls are deployed to protect coastal assets. Alternatively, in some areas there may be a slow retreat of the coastline with few effects on beach ecosystems.

Concerning management, both mitigation and adaptation strategies are needed to meet public ESD goals. The former would seek to constrain the increase in atmospheric greenhouse gases by addressing the underlying causes (i.e., population and economic growth) and by applying appropriate technologies. Adaptation strategies would recognise the linkages between beaches, dunes and surf zones and maintain sand movement and storage and allow for the landward migration of beaches. Failing this, the active maintenance of beaches in their present location by soft engineering (e.g., the transport of sand to the intertidal beach from elsewhere, a process called beach nourishment) is far preferable to hard engineering (e.g., sea-walls) from the nature conservation and socio-economic points of view. Since beach ecosystems are poorly understood even at basic descriptive levels, future management, monitoring, and predictions of the possible impacts of large-scale phenomena (such as global climate change) will be assisted by basic research into documenting biodiversity, community dynamics, autecology, and eco-physiology of beach fauna and the linkages with adjacent ecosystems. As well, the use of human interventions (e.g., beach nourishment) as scientific experiments combined with optimised monitoring is recommended.

Key words: climate change, sandy beaches, ecology, management.

Introduction

Australian intertidal sandy beaches are both numerous (there are about 8,000 ocean beaches (Short and McLeod 1996)), and highly valued for socio-economic reasons (Batley and Cocks 1992; Blackwell 2003; Blackwell in press). Indeed, beaches have iconic status in Australian culture. Less known and valued is the ecological significance of sandy beaches even though they contain numerous plant and animal species (Dexter 1983a, 1983b, 1984, 1985; Brown and McLachlan 1990; Hacking 1998;

Nicholas and Trueman 2005). This ignorance arises because most species are small, buried and inconspicuous. Yet while many species have relatively small abundances, the exoedicerotid amphipod crustaceans *Exoediceros fossor* (Stimpson 1856) and *Exoediceroides maculosus* (Sheard 1936) can attain densities exceeding 10,000 per square metre (Jones *et al.* 1991).

Beaches are thus far from being the ecological deserts of popular belief. Rather, they are living ecosystems

that deserve credible, scientifically-based management in order to promote socio-economic ends. These include the protection of biodiversity and ecological integrity, stated goals of the ecologically sustainable development (ESD) process adopted by all levels of government in Australia (Council of Australian Governments 1992) and applicable to coastal management (e.g., Commonwealth Coastal Policy 1995, New South Wales Coastal Policy 1979 amended 1997).

Unfortunately, coastal management is compromised by the paucity of scientific research on Australian sandy beach ecology which remains "grossly under-represented in our published work" (Fairweather 1990 p.71). Brief reviews appear in Robertson (1994), Jones and Short (1995), and Haynes and Devlin (1997). Rectifying this situation is becoming increasingly urgent because of extensive coastal development in many parts of Australia. In addition to the 85% of Australians now living within 50 km of the coastline, there is a large and continuing internal migration to the coast (ABS 2003). This "suburbia by the sea", wherein some areas are expecting population increases of 54% by 2012 (Oakeshott 2003), imposes numerous developmental, recreational and pollution pressures on beach ecosystems (see Brown and McLachlan 2002 for a review).

On top of this coastal overdevelopment is the burgeoning threat of climate change caused by the enhanced greenhouse effect. This is recognised as a threatening process in Schedule 3 of the NSW Threatened Species Conservation Act, 1995. Coastal ecosystems are particularly vulnerable to climate change since they will bear the brunt of consequent sea-level rise, larger storms and storm surges, and changed wave climates and sediment budgets (CSIRO 2002; Cowell et al. 2006). Indeed, recent modelling suggests that Sydney's shoreline may recede by more than 100 metres by 2095 (Anon 2005). Such events will threaten the very existence of sandy beaches and their biota. Other greenhouse-related factors include changes to the atmosphere (e.g., depleted ozone), water (e.g., temperature, pH, circulation), to precipitation, and possible changes in the linkages between beaches and adjacent habitats (Kennedy et al. 2002).

This paper briefly introduces some sandy-beach ecology and habitat linkages, explores some of the likely ecological effects of climate change, discusses consequent management issues and proposes some biological research. Substantial uncertainty concerning both the extent of climate changes and consequent ecological effects is acknowledged.

Sandy-Beach Ecology

Hundreds of species inhabit sandy beaches but most are rarely noticed since they are small (less than a centimetre long) and live beneath the sand surface. They include primary-producing microscopic algae (mostly episammic and epipelic diatoms), decomposers (bacteria and fungi) and invertebrates (mostly nematodes, crustaceans, polychaetes and molluscs). The invertebrates are often grouped on the basis of size, the meiofauna being less than half a millimetre long and the macrofauna being larger. The former occupy interstitial spaces between

sandgrains and comprise far more species (> 600) than the macrofauna (Brown 2001). These sandy-beach dwellers exhibit remarkable physiological, morphological and behavioural adaptations to changing conditions. For example, many macrofaunal species move and burrow rapidly, are omnivorous feeders and exhibit tidal migrations (Brown and McLachlan 1990; Hacking 1996; Jones et al. 1998). Other beach biota include episodic visitors such as turtles and seabirds, species that depend on beaches for feeding and/or nesting purposes.

To date, most sandy-beach ecologists have addressed structural rather than functional questions and have concentrated on descriptive-correlative studies at various spatial scales. At small, within-beach scales, an important distributional paradigm is that of across-beach zonation with different zonation schemes based either on physical factors (e.g., degree of saturation of the sediments) or biological distributions being proposed (see McLachlan and Jaramillo 1995 for a review). In general, the low shore is richer in species than the high shore and different species dominate in different zones (see Dexter 1984; Hacking 1996; James and Fairweather 1996 for Australian examples). However, the term "zonation" may be inappropriate because the across-shore distributional boundaries of sets of species may not coincide (Hacking 1996). Further, many species migrate tidally across the shore causing any biologically-defined "zones" to vary with tide height.

At larger, between-beach scales, there are ecological differences associated with the degree of wave action and its interaction with grain size and slope of beaches. These physical factors have led to the classification (really a continuum) of beaches into reflective, intermediate and dissipative types (Short and Wright 1984). Exposed, reflective beaches are steep with a narrow swash zone, coarse particles, little organic and water content, and waves that break abruptly in the intertidal zone. They differ from exposed dissipative beaches which are flat with a wide swash zone, fine sand with large water content and steeper vertical physico-chemical gradients, and waves breaking far from shore. Dissipative beaches have a greater richness of species and total abundance and biomass and more soft-bodied species such as polychaete worms. In extreme cases, reflective beaches may support no macrofaunal species at all (McLachlan et al. 1995). Global patterns of species richness are correlated with composite indices such as the Beach Index of McLachlan and Dorvlo (2004) which is based on tide range, beach slope and particle size.

Since most patterns are correlated with physical factors rather than biological factors, it is likely that physical factors are most important in structuring the ecological assemblages. i.e., they are "physically controlled" rather than "biologically accommodated" (Brown and McLachlan 1990; Jaramillo and McLachlan 1993). Indeed, Brown et al. (2000) state that wave action is the super-parameter controlling South African sandy-beach ecology, suggesting the applicability of the "autecological hypothesis" (Noy-Meir 1979; McLachlan 1990) in which species in physically-controlled habitats respond individualistically to physico-chemical factors.

Similarly, the ecological differences between reflective and dissipative beaches were attributed to the hydrodynamic force in the swash zone i.e., the "swash exclusion hypothesis" (McLachlan *et al.* 1993). Recently, this has been extended into the "multicausal severity hypothesis" (Brazeiro 2001) and the "habitat harshness hypothesis" (Defeo *et al.* 2003). The former incorporates the additional physical factors of grain size, organic matter and erosion-accretion dynamics while the latter combined the autecological hypothesis with the swash exclusion hypothesis. It predicts a "decrease in the performance of sandy beach macrofauna descriptors at the community (lower species richness, diversity, abundance) and population (lower abundance, growth in weight and length, fecundity, reproductive output and higher mortality rates) levels from dissipative to reflective conditions." (Defeo *et al.* 2003, p.353). A consequence of physical control is that the loss of any particular species would have little effect on others, unlike biologically-accommodated assemblages where cascading effects may follow the loss of key species e.g., Schiel *et al.* (2004).

While the claim of physical control is plausible, it is also questionable since the explanatory models have not been tested via controlled experimentation, largely because of feasibility problems in an energetic and unstable environment. Moreover, recent studies have indicated the influence of biological factors. For example, the autecological predictions of the habitat harshness hypothesis were not supported empirically for two Uruguayan species by Defeo *et al.* (2003) who suggested (p.352) that "biotic mechanisms could be of utmost importance in dissipative beaches". This conclusion is supported by studies that have suggested or demonstrated the effects of competition in the yellow clam *Mesodesma* (Defeo 1998; Brazeiro and Defeo 1999), density-related effects on burrowing in *Donax* (McLachlan 1998, Dugan *et al.* 2004) and the trophic role of macrophyte wrack whose quantity was significantly correlated with the species richness, abundance and biomass of wrack-associated fauna and the abundance of predators such as shore birds (Dugan *et al.* 2003). Moreover, poorly-designed beach nourishment interventions have the potential to suppress macrofaunal recovery with upwards cascading reductions on other beach biota (Peterson *et al.* 2006).

Consequently, both physical and biological factors play ecological roles on sandy beaches although the relative importance of various factors and mechanisms in explaining distributional patterns may vary with beach type and is not well established. This knowledge deficit hinders attempts to predict the effects of events such as climate change and to recommend management responses although the patterns and assemblage-level correlations mentioned above provide an inductive basis for prediction.

Habitat Linkages

Sandy beaches have functional ecological linkages with adjacent ecosystems, especially sand dunes and the surf zone (Brown and McLachlan 1990). Indeed they are sometimes considered a single ecological unit (e.g., James 2000a). Links also exist with estuaries and coastal lagoons. These include the exchange of sand, organic matter and nutrients (Short and Hesp 1982) and the sharing of some species (Gladstone *et al.* 2006).

These links are important because beaches, being unstable, have no large attached plants to provide food or habitat for animals. Instead, much primary production is imported via surf-zone phytoplankton and stranded macrophytes (Koop *et al.* 1982; Dugan *et al.* 2003). The former are consumed by filter-feeders and the latter are decomposed by bacteria and fragmented by the grazing of small invertebrates (e.g., isopods, amphipods and insect larvae). The nutrient-rich faeces of these invertebrate consumers are utilized by the beach bacterial community or transported back to the sea (McLachlan *et al.* 1981). The bacteria support faunal members of the beach trophic system that, in turn, support more conspicuous beach species such as sea birds.

Other ecological links include the long-distance migrations of birds and turtles (Bouchard and Bjorndal 2000; Colombini and Chelazzi 2003), the movements of planktonic larvae of beach adults in ocean currents, and the effects of estuarine discharge which can influence the abundance of bivalve molluscs (Donn 1987; Schoeman and Richardson 2002). As well, some fish species use surf zones as nurseries (Lenanton and Caputi 1989; J.M. Leis pers. com.) and feed on beach invertebrates (Du Preez *et al.* 1990). A consequence of these linkages is that they must be accommodated as a major part of ecosystem-based management.

Environmental Consequences of Climate Change

The many effects of climate change on the coastal zone have been categorised by Cocks and Crossland (1991) into primary changes (higher atmospheric CO_2 concentrations and air temperatures), consequent second-order effects (e.g., warmer water with reduced pH), third-order (e.g., sea-level rise and changed hydrology) and lower-order effects (e.g., beach erosion, coastal retreat, biological changes). Dunes and beachfronts were included among the "vital areas" that would be lost or experience dysfunction via multi-order effects (Cocks and Crossland 1991). Additional listings and discussion of ecological effects appear in IPCC (2001), Brown and McLachlan (2002), Kennedy (2002), International Scientific Steering Committee (2005) and Harley *et al.* (2006). Some effects on beach biota may be direct such as the physiological effects of temperature rise; others may be indirect e.g., the effects of oceanic acidification on surf-zone phytoplankton that provide food for some beach species, and trophic cascades. Yet others may arise from the interaction of factors e.g., sea level rise, storm surges and human activities may combine to exacerbate sand erosion.

Unfortunately, there is much uncertainty surrounding the entire greenhouse issue. This includes the extent and rate of climate change itself, its effects on sea levels, storminess, wave climates, water temperature, water chemistry, physical beach processes and ecological predictions (IPCC 2001; Brown and McLachlan 2002; CSIRO 2002; Cowell *et al.* 2006). Despite this, some ecological responses to climate change (e.g., changes in phenology, physiology, range and

distribution, assemblage composition, species interactions and the structure and dynamics of ecosystems) are now documented (Walther *et al.* 2002; Hughes 2003, Harley *et al.* 2006). Moreover, scenarios corresponding to different magnitudes of change in temperature, pH and sea-level rise appear in International Scientific Steering Committee (2005), these predictions being made with varying degrees of confidence. For example, there is more confidence concerning the effects of temperature on physiology, abundances and distributions than on biotic interactions (Kennedy 2002). Included below are some predicted abiotic environmental changes and their likely ecological consequences.

Temperature change

By 2070, annual average temperatures over Australia are projected to rise by 1.0 – 6.0°C relative to 1990 and changes in extreme temperatures are also expected (CSIRO 2002). Presumably, rises in water temperature would be less than for the air and the extremes would be lower. Nevertheless, even small changes may have large ecological consequences with the IPCC (2001) judging that rises beyond 2° C are unacceptable for ecosystems and biodiversity. This was revised downwards by Leemans and van Vliet (2005) to 1.5°C with the rate of change limited to less than 0.5°C per decade. Since temperature is a master factor limiting species' distributions (Krebs 1978), and some species are sensitive to small temperature increases (Kennedy 2002), there is likely to be a poleward shift in intertidal species' distributional boundaries with the replacement of coldwater species by those from warmer waters (Kennett and Stott 1991). As well, alongshore distributions may be altered by a 'squeeze' effect (Harley *et al.* 2006). Here, abiotic stress may alter vertical zonation patterns such that a given species may be displaced (squeezed) by another species moving into its zone. The assemblage composition on any shore would thus also change (Southward *et al.* 1995; Schiel *et al.* 2004) although this is not necessarily a cause for concern since variation in the composition of biotic assemblages is normal and assemblage diversity and function may change little.

The species most affected would be those now living close to their upper thermal limit and unable to acclimate or adapt. They would become locally extinct and survival would depend on migration to cooler areas. This may be more difficult for intertidal species than oceanic species (IPCC 2001), especially those lacking dispersal larval stages e.g., peracarid crustaceans, a dominant component of Australian sandy beach macrofauna (Dexter 1983a). Narrow-range endemic species would be at particular risk. In Victoria, 3.7% of coastal marine invertebrates are endemic to the region and some of these are limited to cool-temperate waters (O'Hara 2002). These species would be threatened by a 1-2°C rise in temperature although changes to the assemblage structure may arguably be balanced by the immigration of northern species. At greatest risk would be the species endemic to south-eastern Tasmania that cannot migrate to cooler waters (Edgar *et al.* 1997). Such species may become globally extinct as predicted for terrestrial species in

equivalent circumstances (Hughes 2003). Consequently, higher temperatures may have different distributional implications for different latitudes and for taxa with different dispersive abilities.

While some ecosystems have already experienced substantial temperature-related changes (Walther *et al.* 2002; Hughes 2003), Brown and McLachlan (2002) considered that the effects of temperature rise on sandy beaches will be "subtle rather than dramatic" (p.71) since water temperatures will rise less than the air, many species can burrow to evade extreme heat, and the change may be sufficiently gradual to allow acclimation. However, other processes such as photosynthesis, decomposition and nutrient recycling will probably be accelerated by temperature rises as a product of the Q_{10} law. This would enhance productivity which may, in turn, permit larger populations and greater species richness. Alternatively, the faster decay of beach wrack may enhance the de-oxygenation of the underlying sand with deleterious effects for some species as explained below. And reproductive processes may be affected. For example, the sex ratio in the painted turtle (*Chrysemys picta* Schneider, 1773) is temperature dependent and a rise of 2-4 degrees may compromise the production of male offspring (Janzen 1994).

Indirect effects of temperature change on the beach biota may also occur. For example, a rise of 0.6 °C was associated with major changes in planktonic ecosystems in the North Sea (Richardson and Schoeman 2004). Given that the plankton is a source of food for some adult beach species and/or their larvae, it is likely that the beach biota will be affected by planktonic changes. Secondly, increased water temperatures will cause reduced dissolved oxygen, a factor likely to be influential in some demersal, stratified situations (Kennedy 2002). However, this is unlikely in the energetic, wave-driven intertidal habitat.

Finally, temperature can also affect species interactions such as shifts in food webs (Kennedy *et al.* 2002). However, little is known concerning sandy beaches although changes in the biomass of macrophyte wrack can have cascading effects (Dugan *et al.* 2003).

Sea-level rise

Sea-level rise will cause geomorphic adjustments to coasts (Cowell and Thom 1994). Sand will be eroded from the upper beach and deposited on the near-shore bottom, causing the shoreline to recede horizontally at 50 -100 times the vertical sea-level rise i.e., the so-called "Bruun Effect" (Bruun 1962). By 2100, recession would be 4.5 – 88 metres (CSIRO 2002) but this may be an underestimate for some of Sydney's beaches (Anon 2005). Overall, this means that currently-retreating beaches (approximately 70% of global sandy beaches are retreating, 20-30% are stable, and less than 10% are accreting) will retreat further, stable beaches will begin to retreat, and the number of accreting beaches will decrease (Burkett *et al.* 2001). This is unlikely to have large ecological effects if a landward retreat by beaches is the only change. However, if there are accompanying changes to dunes, wave climate, grain size, beach area and slope, large ecological effects would occur on a given beach.

If dunes become eroded or destabilised at a fast rate, dune vegetation would be lost. This loss would further increase erosion creating a destructive positive feedback loop until sea-level rise stabilised. Such losses would directly affect any dune fauna using vegetation as habitat or food and indirectly affect beach fauna since the supply of organic matter to the upper beach would fall. Turtles and seabirds that nest in dunes would be severely affected.

If particle size and beach slope (i.e., morphodynamic state) change, the richness, abundance and kinds of macrofauna will change since steep, reflective beaches are impoverished compared with flat dissipative beaches. Similar ecological consequences may arise if climate change enhances alongshore sediment transfer via changes in the directional weightings of the wave climate i.e., "Gordon Effects" (Cowell and Thom 1994). Shoreline stability is even more sensitive to Gordon Effects than Bruun Effects (Cowell and Thom 1994).

As well, if hard engineering, (e.g. sea-walls and groynes), is used to defend societal assets against erosion, the local sandy-beach habitat would be fundamentally altered, perhaps removed entirely. Consequently, the main ecological effects of sea-level rise are likely to be caused by change to, or loss of habitat. Not only would the permanent sand-dwelling biota be affected but also the visitors such as seabirds and turtles. However, the meagre literature on the ecological effects of sea-walls produced conflicting results. For example, while the ocypodid ghost crab (*Ocypode cordimanus* Desmarest, 1825) in New South Wales appears to be badly affected (Barros 2001), the macrofauna of a Chilean beach showed no significant effects (Jaramillo *et al.* 2002). The ecological consequences of sea level rise and/or increased storm frequency may be exacerbated on beaches already managed with hard engineering. For example, groynes on open beaches accumulate sand in their vicinity but also lead to downdrift erosion (Peterson *et al.* 2000). This has led to the loss of beaches on many sections of the European coastline (Speybroeck *et al.* 2006). The increased downdrift erosion likely to occur under conditions of higher sea levels and more frequent storms will lead to loss of significant areas of beach habitat.

Of course, any erosion-based effects may be ameliorated by managed nourishment or by the formation of new beaches via accretion. Alternatively, beaches with extensive dunes and available setbacks may change little other than migrating landwards.

Climate variability

It is likely that some aspects of climate will become more variable. For example, global climate change may cause changes in large-scale ocean-atmosphere interactions and an increasing frequency of El Niño conditions. These have been related to cyclic changes at Narrabeen Beach (Sydney) which accretes at its southern end when the Southern Oscillation Index (SOI) is positive because of an increased prevalence of east to northerly waves. When the SOI is negative and there is an increased prevalence of southerly waves, the northern end of the beach accretes and the southern end erodes (Short

et al. 2000). An increased frequency of El Niño-like conditions associated with global warming will lead to changes in shoreline position.

As well, storms may become more intense (IPCC 2001; CSIRO 2002). Their interaction with sea-level rise and spring tides would probably cause sufficient erosion to decimate both beach and dune biota. While the intertidal beach invertebrates may recover rapidly (Ansell 1983), the dune effects may persist if erosion removed attached dune plants and their dependent fauna (Brown and McLachlan 2002; DLWC 2001). Birds such as the Little Tern (*Sterna albifrons* Pallas, 1764), Pied Oystercatcher (*Haematopus longirostris* Vieillot, 1817), Beach Stone-Curlew (*Esacus neglectus* Mathews, 1912), Hooded Plover (*Thinornis rubricollis* (Gmelin, 1789)) and Red-Capped Plover (*Charadrius ruficapillus* Temminck, 1822) would be at risk since they nest in the supralittoral (Annette Harrison, pers. comm.) as do the Green Turtle (*Chelonia mydas* Linnaeus, 1758) and Leathery Turtle (*Dermochelys coriacea* Linnaeus, 1766). Most of these species are already under threat, being listed in Schedule 1 of the NSW Threatened Species Conservation Act, 1995.

Increased storminess would also enhance wave energy and therefore may change the morphodynamic state of the beach with consequent ecological changes as outlined above. In addition, settlement and recruitment may be affected by changes in grain size composition and beach slope. For example, the South African wedge clam *Donax serra* (Röding) settles as spat in the surf zone, preferring areas with more fine sediment. They grow and then recruit into the adult population on the intertidal beach, this being influenced by the beach slope (Schoeman and Richardson 2002). The amount of fine sediment in the surf zone and the beach slope is likely to be influenced by the frequency of storm surges and sediment inputs from the catchment. Other climate-related population changes involve the distribution and abundance of the sandhopper *Talitrus saltator* (Stimpson, 1852) on the Baltic coast (Weslawski *et al.* 2000). It now occurs in fewer localities and at lower densities compared with previous records, a pattern correlated with increases in storm frequency, winter severity and sea level.

The predicted changes in beach sedimentology – arising for example from changes in estuarine outflow – may lead to changes in the composition of infaunal invertebrates and to altered trophic interactions. Studies of the distribution and abundance of infaunal invertebrates have revealed a strong association with sediment grade (Gray 1974; Peterson and Bishop 2005; Peterson *et al.* 2000). Peterson *et al.* (2006) found that fewer shorebirds (e.g. sanderling) foraged on beaches with anthropogenically modified sediment composition and attributed this change to the reduction in density of the sanderlings' prey (*Donax* spp. surf clams) that followed the modification. There are other ways that shorebird foraging on beaches may be impacted by changes in sediment grade. Foraging efficiency may be adversely affected by a change in sediment composition via impacts on shorebirds' ability to probe modified sediments with their bills and to manipulate prey (Quammen 1982; Peterson *et al.* 2006).

It was hypothesised under *Oceanic acidification and carbonate chemistry* that changes in seawater chemistry may reduce the calcification of the shells and exoskeletons of beach organisms. Support for the possibility of trophic cascades arising from this comes from studies showing that the shell thickness of molluscs affects their susceptibility to breakage (Vermeij 1979) and presumably their vulnerability to predators such as fishes, crabs and shorebirds.

In general, increased wave energy should impose a greater metabolic cost on species attempting to maintain their position in the swash zone, with flow-on effects to reproduction, survival and population replenishment. However, a recent study of the burrowing anomuran crab *Emerita analoga* (Stimpson,1852) found no difference in oxygen uptake (a measure of physiological stress) by crabs across a range of wave exposures on the same beach (Lastra *et al.* 2004). The lack of an effect suggests acclimation to changes in wave energy by this species.

Another likely consequence of increased storminess involves the linkages between the intertidal beach and adjacent areas. Approximately 12% of kelp biomass is broken off during average storms and most is deposited on beaches as wrack (Griffiths and Stenton-Dozey 1981). Bigger and/or more storms would probably produce more wrack with contrasting effects on beach fauna (McGwynne *et al.* 1988). Firstly, it would lead to more localised hypoxia via decomposition. If the redox discontinuity layer rises, or if "methane geysers" develop underneath dense wrack accumulations, both macrofauna and meiofauna would be reduced or eliminated (McLachlan 1985; Hacking, unpublished data). However, recovery should occur once the wrack is gone and the pore-water re-oxygenated. As well, since stranded kelp affects both the feeding and burrowing efficiency of the wedge clam, *Donax serra* (Soares *et al.* 1996), large-scale wrack increases will probably reduce the abundance of this clam.

Secondly, species likely to benefit from increases in stranded wrack include those that depend on wrack for food or habitat (e.g., insect larvae, amphipods and their predators – Dugan *et al.* 2003) and species that benefit from the insulation it provides to the underlying sand. Wrack piles insulate the underlying sand from temperature extremes and maintain high humidities throughout the day. This favours beach fauna that have no active mechanism for water retention, such as the amphipod *Orchestia gammarellus* (Moore and Francis 1985).

Increased storminess would also produce increased hydrodynamic energy. In turn this may cause increased near-shore turbidity and decreased surf-zone photosynthesis. If so, this would reduce the food supply for beach fauna, especially on dissipative beaches. Alternatively, more energy may boost coastal upwelling (IPCC 2001), thus transporting more nutrients to the photic zone and boosting photosynthesis. A final consequence of stronger storms is that more shipwrecks may occur causing more pollution. However, this is uncertain in the case of oil pollution since oil will soon become a declining resource.

Oceanographic changes

If climate change alters current systems, numerous species would probably be affected since many migrate either as larvae (most invertebrates) or as adults (e.g., turtles). These changes may arise via changes at large scales (e.g., changes in major current systems) and small scales. The latter includes possible changes in near-shore currents responsible for the deposition of wrack and carrion and local larval transport and retention.

Rainfall changes

Rainfall is likely to increase in some regions and decrease in others (CSIRO 2002). These changes may affect beaches because of their linkages with dunes and lagoons. For example, rainfall may influence the growth of dune vegetation with consequences for dune stability and the exchanges of sand and organic matter with the beach. As well, rainfall changes will alter the frequency of natural openings of lagoons. This may change the supply of sediment and nutrients from terrestrial catchments to the sea and beach. Finally, rainfall changes would alter the level of the water table of beaches. In turn, this is likely to affect the distribution or survival of burrowing species of the upper beach via desiccation.

Oceanic acidification and carbonate chemistry

The enhanced greenhouse effect is largely caused by the addition of CO_2 to the atmosphere. While CO_2 in the atmosphere is relatively inert, it becomes highly reactive when dissolved in seawater and can potentially affect many biogeochemical conditions and processes (Turley *et al.* 2005). In particular the pH of ocean waters will fall. The pH of surface waters is already 0.1 units less than pre-industrial levels and is predicted to decline by a further 0.3 – 0.4 units by the end of the century, changes not seen for about 20 million years (Haugan and Drange 1996; Brewer 1997). Because this will reduce the calcium carbonate concentration, calcification rates will decrease in a range of marine organisms ranging from test-forming phytoplankton to scleractinian corals (Feely *et al.* 2004).

Calcification is also important to beach taxa such as molluscs and crustaceans since they have robust shells, probably to protect them from abrasion or predation. The crustacean exoskeleton is constructed of chitin, lipids and proteins and strengthened by either amorphous or crystalline calcium carbonate. The molluscan shell is constructed from crystals of calcium carbonate dispersed in an organic matrix (Lowenstam 1981; Harper 2000). The calcium carbonate crystals are either aragonite or calcite, there being considerable variation within molluscan families in crystal type e.g. Littorinidae (Taylor and Reid 1990). Aragonite is at least 50% more soluble in seawater than calcite and molluscs with shells constructed from aragonite may therefore be more susceptible to elevated acidification (Mucci 1983; Feely *et al.* 2004). Further research within Australia on the mineralogy and microstructure of the shells of molluscs and the exoskeletons of crustaceans will greatly improve our

ability to predict the possible consequences of seawater acidification on these organisms. However, it is reasonable to assume that many beach species will be particularly vulnerable if their calcium metabolism is compromised.

Increases in the partial pressure of CO_2 in seawater affect the physiology of marine organisms in ways other than calcification. Elevated levels of CO_2 lead to acidosis of tissues and body fluids. Although compensation occurs (through accumulation of bicarbonates), the new steady-state values may have negative consequences for growth and reproduction (Pörtner *et al.* 2004). On the other hand, some species may acclimate to, or tolerate the expected increases in CO_2. These include species with a low activity or with specialized physiology that provides tolerance to high CO_2, or species inhabiting environments that currently experience wide variations in CO_2 and are therefore pre-adapted to some degree of change (Pörtner *et al.* 2004). The intertidal section of sandy beaches experiences daily variations in CO_2 associated with tides. Interstitial CO_2 increases during high tide and decreases during low tide (Pearse *et al.* 1942) and therefore the biota may be pre-adapted. For example, the meiofauna (predominantly nematode and harpacticoid species) of sandy beaches can be tolerant of high temperatures and extreme pH values (Wieser, 1974).

Species able to tolerate temporary changes in CO_2 associated with tidal movements may, however, incur costs (e.g. in growth, reproduction, survival) arising from compensation to permanent elevations of CO_2 (Pörtner *et al.* 2004). The possibility of long-term negative effects is highlighted by recent studies of the role of oscillations in aquatic CO_2 in the Permian Triassic mass-extinction events (Bambach *et al.* 2002; Berner 2002). At present, however, there is very limited understanding of the eco-physiology of intertidal beach fauna.

Management Implications

In Australia, coastal management has received considerable attention (e.g., Commonwealth Coastal Policy 1995; New South Wales Coastal Policy 1979 amended 1997). As part of this, beach management has sought to protect the coast and property and provide for recreation i.e., a "hazards and playgrounds" approach (James 2000b). This draws on the substantial understanding of geomorphology and physical processes (e.g., Short and Wright 1984; Bird 1996; Cowell *et al.* 2006) but contains little about biological objectives. In fact, James (2000a, p. 149) observed that "effective goals for beach management are yet to be thought out and clearly articulated in Australia" and that "a specific policy for beaches should be developed given the importance of beaches in Australia".

Specific objectives that integrate the interacting natural, socio-cultural and management systems (James 2000b) and that apply to both human utility and conservation are required. Concerning climate change and biodiversity, the National Biodiversity and Climate Change Action Plan 2004-2007 (www.deh.gov.au/biodiversity/publications/nbccap/objectives.html) has proposed seven objectives. Of these, objective 4 is "to minimise the impacts of climate change on marine, estuarine and coastal ecosystems". While various strategies concerning adaptation (coping with unavoidable impacts) are included, mitigation strategies (minimising future impacts) are absent. Yet, major investment in both kinds of strategy is needed now (International Scientific Steering Committee 2005).

Ideally, the principal mitigation strategies would seek to halt or even reverse climate change via large reductions in greenhouse emissions to the atmosphere. Suggested approaches include the rapid development and deployment of cleaner energy sources and the sequestration of CO_2 underground. Less accepted but arguably more important would be easing the underlying drivers of climate change i.e., stabilising or reducing the human population and reducing greenhouse-causing economic activity. Unfortunately, the task is daunting because of the large current greenhouse momentum, the reluctance of some developed countries to seriously address the issue, the rapidly-expanding human population, the human pre-occupation with short-term benefits and particularly the universal quest for energy-demanding economic growth. The last is exemplified by Australia's Prime Minister, John Howard who said "the idea that we can address climate-change matters successfully at the expense of economic growth is not only unrealistic but also unacceptable" (reported in Breusch 2006). Moreover, recent reports claim that the "worst fears about global warming and rapid sea-level rise will be realised or exceeded" (reported in Denholm 2006) and that "international action to halt climate change must be taken within 20 years or global warming will be irreversible" (reported in Anon 2006).

Adaptive measures accept the reality of sea-level rise and coastline retreat and seek to increase coastal resilience, a concept with ecological, morphological and socioeconomic components (IPCC 2001). Unfortunately, coastal resilience has been impaired by anthropogenic effects on the sediment budgets of beach-dune systems (Tomlinson 2002; Alonso and Cabrera 2002; Sherman *et al.* 2002). Measures to promote resilience include the protection, vegetation and stabilisation of dunes, maintenance of sediment supply and the provision of buffer zones, rolling easements or setbacks that allow the landward migration of the coastline. Such managed retreat strategies have been adopted by several countries including Australia (see e.g., the State Coastal Planning Policy of Western Australia 2003 for an example of setback planning to accommodate sea-level rise).

But all these strategies have their limitations. For example, although dune management is regarded as a prime coastal management tool (Tomlinson 2002), it would, at best, retard the retreat of the coast. Further, setbacks involving buyouts may be extremely expensive and socially unacceptable in areas where substantial coastal societal assets already exist e.g., in urban areas. In these circumstances, society may attempt to protect assets via engineering solutions such as large-scale beach nourishment and/or the construction of sea-walls. Unfortunately, the latter would probably cause the total loss of the beach (as for example in New Jersey, U.S.A.) with consequent large economic losses (Blackwell 1997). Alternatively, since nourishment can maintain beaches in

a semi-natural state, it is arguably far preferable for both economic and conservation purposes and is now the method of choice (Finkl and Walker 2004). However some caveats apply. For example, if the replacement sediments fail to match the original sediments, ecological recovery is retarded or prevented (Nelson 1993, Bilodeau and Bourgeois 2004, Peterson and Bishop 2005, Peterson *et al.* 2006)

Given accepted ESD objectives (one of which entails the protection of biodiversity and ecological processes), the sea-wall approach represents a complete failure of ecological management since the entire beach habitat may be lost. Moreover, it may provide effective protection only in the short term. In the long term "our coastal communities may have to rethink their location and may be forced to consider a retreat from the beach" (Tomlinson 2002).

Finally, credible management needs sufficient scientific knowledge to successfully attain stated visions and objectives and establish efficacious indicators. Unfortunately, the ecological knowledge base for Australian beaches is currently very small compared with other coastal ecosystems (Fairweather 1990, James 2000b). Consequently, it is important to adapt ideas from both overseas work (Brown and McLachlan 1990) and general ecosystem management principles (e.g., Grumbine 1994; Australia's Ocean Policy 1998; Sherman and Douda 1999; McLeod *et al.* 2005). In these circumstances of substantial ignorance, an adaptive management approach in which predictions are tested scientifically and management corrections made where necessary will be important as will the liberal application of the precautionary and onus principles (Dovers and Handmer 1995). None of this is to claim that an adequate scientific basis for management exists. Certainly there is a pressing need for focussed research both in Australia and overseas.

Recommendations for Research

The suggestions presented below address some basic ecological questions and some major impact issues related to climate change and beach management. As a starting point, predicting the effects of climate change requires a research emphasis on the basic ecology of beach biodiversity. This will, in turn, support the development of realistic modelling scenarios. The following list of research priorities is therefore general but points to the ecological questions that will assist further understanding of the possible effects of climate change. Recommendations relate not only to the direct, individual effects of climate-change factors such as changes to habitat, temperature and pH, but also to their indirect, interactive effects with other factors that are likely to become more important, especially beach nourishment and hard engineering.

Documentation of assemblages. This includes their structure and composition, and patterns and ranges of natural variation in distribution and abundance. Such descriptions underpin logical frameworks involving explanatory models and predictive hypotheses. And they provide a baseline against which the ecological health/integrity of beaches under stress can be evaluated. Moreover, large-scale biogeographical information is needed to optimise the siting of reserves.

Trophic ecology. Investigations needed include (1) the feeding ecology of infaunal invertebrates and foraging shorebirds and fishes; (2) the ecological and biogeochemical processes determining the distribution and abundance of infaunal invertebrate prey and (3) the nature, sources, dynamics (spatial and temporal), and ecological roles of externally-produced inputs (e.g. macroalgal wrack) to beaches.

Linkages. Some sandy-beach species depend on linkages with adjacent systems such as dunes, surf zones and estuaries. Research elucidating these links, especially under climate-change scenarios, would assist beach management. For example, the trophic and distributional effects (via larval transport) from changes in nearshore currents and upwelling resulting from climate change Secondly, it is probable that increased storminess will enhance the import of macrophyte wrack to the beach with large ecological consequences (Dugan *et al.* 2003). Thirdly the nature, extent and ecological significance of connectivity between beaches and estuaries (including intermittently opening estuaries) and the consequences of alterations to estuarine outflows may be important.

Biological interactons. Sandy beaches have traditionally been assumed to be physically controlled with the implication that biological interactions are unimportant for the maintenance of biodiversity. However, recent work has challenged this assumption. If particular species have large influences on others, these need to be identified and managed and could become the focus for monitoring.

Life cycles. Knowledge of reproductive biology, life cycles and dispersal abilities can guide the timing of beach engineering projects and inform predictions about recovery from major stresses/disturbances. Such knowledge also helps to define the spatial scale at which beach management should operate.

Dune plants. Since dune plants assist in the stabilisation of dunes and provide organic subsidies to beaches, basic and applied ecological knowledge is valuable.

Habitat loss. Since it is likely that many beaches will be lost due to sea-level rise and sea-wall construction, loss of habitat will be a major issue. In order to maintain beach biodiversity, it will be necessary to select beaches that will be allowed to migrate inland. To optimise the siting of these beaches, basic biogeographical information on numerous species is needed along with information on their life-cycle, colonising ability, and the sources and sinks of colonists after large disturbances at individual beaches.

Temporal ecological change. In order to assess climate-related temporal change, a program of monitoring is necessary. Since this could be unacceptably expensive, a toolbox of methods should be developed to optimise efficiencies. This would entail the identification of suitable indicator taxa, the establishment of socially-acceptable or ecologically-significant effect sizes that would allow monitoring to be cast as a hypothesis-testing exercise, sampling designs that would have the statistical power to detect the effect size, and the determination of a reasonable sampling frequency.

Individual and interactive forcing factors. Eco-physiological experiments on the individual effects of change in factors such as temperature and pH will facilitate the development of predictive models. Complicating this is the probability of enhanced effects caused by the interactions among factors i.e., multiple stresses. For example, the effects of pH change may interact with increased temperature or storminess. Other issues include the ability of species to acclimate to change in the short term or, since climate change is a slow process, the prospect of genetic adaptation.

Adaptive management. Human interventions that are likely to increase as a result of sea-level rise can be studied as experiments. Such an approach is likely to be more effective in policy development than alternatives (Healey and Hennessey 1994). Coastal interventions include hard and soft engineering projects with the rise of beach nourishment

being particularly important (Peterson *et al.* 2006). Important components of adaptive management include the specification of the magnitude of socially-unacceptable or ecologically-significant impacts, monitoring to detect these impacts and, where necessary, the identification of superior alternative management strategies.

Modelling studies. The potential impacts of climate change on beach biodiversity, engineering and human usage of beaches could be modelled.

The above are a few suggestions for beach research that would inform management. Many others exist and most would benefit from multidisciplinary approaches since a range of physico-chemical-biological questions are involved. Moreover, liaison with other stakeholders, especially managers would enhance the effectiveness of much research (Von Koningsveld *et al.* 2003).

Acknowledgements

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APPENDIX I

Beach nourishment operation at Lady Robinson's Beach, Botany Bay. Sand is dredged from offshore (see dredger in background), pumped as a slurry to the beach (see pipe in foreground) and contoured by front end loader.

Photo: A. Jones

The sandy-beach exoedicerotid amphipod *Exoedicerus fosser*.

Photo: R. Springthorpe

Beach erosion at Towra Point, Botany Bay.

Photo: A. Murray